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Late Miocene increase in precipitation in the Western Cordillera of the Andes between 18–19°S latitudes inferred from shifts in sedimentation patterns

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A B S T R A C T

Modern climate in the Andes is characterized by strong N–S decreasing trends in precipitation rates. Here we use stratigraphic records to show that this pattern has been established since as early as 12–11 Ma, at least on the western Andean margin of Northern Chile. The stratigraphic architecture on the western Andean margin documents a transition between 19°–20°S latitude where matrix-supported debris flow deposits shift to fluvial conglomerates between 12–11 Ma. The deposition of fluvial sediments has been maintained to the present north of 19°–20°S, while the occurrence of post 11 Ma aeolian sand, matrix-supported breccias with conglomerate interbeds south of these latitudes implies ongoing sedimentation with less water and thus under drier conditions. We relate these changes to the tectonic development of the Andes. Existing palaeoclimate models suggest that an elevated plateau deflects the Andean jet towards the south, thereby focusing moisture from the equatorial Atlantic to the northeastern flanks of the Altiplano. In addition, the formation of the eastern Andean foothills most likely intercepted moisture transport, and shifted it farther to the east, thereby keeping the western Andean margin dry south of 19°–20°S latitudes. The sedimentological data support a strong linkage between orographic precipitation and stratigraphy whereby central Andean deformation controls the distribution of available moisture on the western flank through a combination of orographic precipitation and deflection of air masses.

1. Introduction

The central Andes between c. 16°S and 24°S latitude are characterized by large climate contrasts with tropical conditions on the eastern side, and an extremely dry climate on the western margin (Fig. 1A). Likewise, precipitation rates reveal large N–S gradients, resulting in semiarid conditions on the western margin in northern Peru and in a hyperarid climate in northern Chile. These trends where modern precipitation rates decrease from N to S are particularly evident in water budgets, where annual precipitation north of 17°S is large enough to supply the perennial Lago Titicaca (Fig. 1B). However, dryer conditions farther south have resulted in the establishment of salt pans in the Lago Poopó at 19°S and the accumulation of evaporites in the Salar de Uyuni at 21°S. The effects of such precipitation gradients are also evident on the western Andean margin (Fig. 1B), with the result that modern runoff of streams with sources in the Western Cordillera (Houston, 2006) shifts from perennial north of 19°–20°S, to semi-perennial and ephemeral south of 21°S, as reported by Nester et al. (2007, see their SI Table 2). Although evidence for N–S precipitation gradients exist, the timing of their formation, and the mechanisms through which these changes occurred have been contested.

In the past years, sedimentological data from the endorheic Central Depression, situated south of c. 19.5°S between the Western and Coastal Cordilleras (Fig. 2), have been used to infer a semi-arid/arid climate on the western Andean margin at least since Late Miocene times, and possibly earlier (Jordan et al., 2014). In this context, Armijo et al. (2015) interpreted that shifts to hyperarid conditions in northern Chile occurred as a response to global cooling after the Mid-Miocene climate optimum (Zachos et al., 2001). For the time after 4 Ma, Hartley (2003) and also Jordan et al. (2014) suggested that a further enhancement of the already existing hyperarid conditions in western South America established as consequence of an additional phase of global climate cooling, but both authors did not rule out the possibility of oro-

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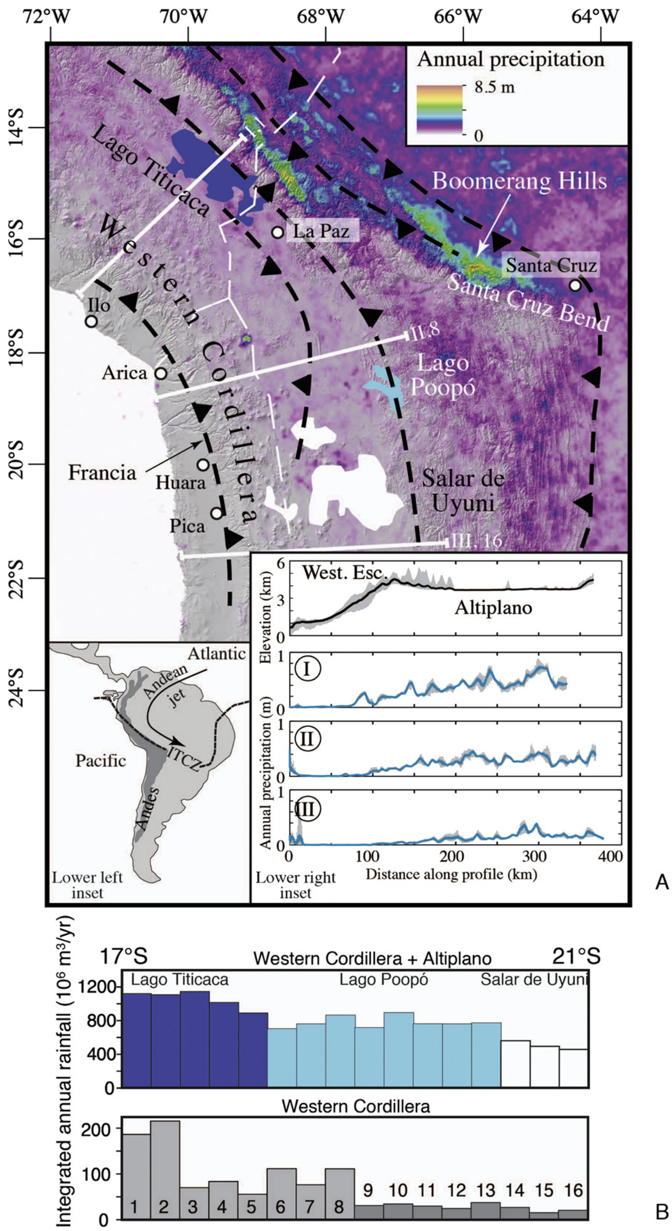

Fig. 1. (A) Central Andes with pattern of annual precipitation. The inset map (lower left side) shows the course of the Andean jet. I, II and III in lower right inset indicate sections (swaths 1, 8 and 16 of Fig. 1B) for which 10-km-wide precipitation swath-profiles are shown in inset figure on the lower right side. Precipitation data are the 2B31 TRMM data set (Mulligan, 2006). Satellite images © Google 2015. (B) Mean annual water budgets for 16 swaths across the Andes. See Fig. 1A for location of swaths 1, 8 and 16. Water budgets were calculated as the products between mean annual precipitation rates (extracted from the 2B31 TRMM data set) and the area. No evapo-transpiration nor infiltration has been considered for these calculations. Swath 1 corresponds to section I on the lower right inset of Fig. 1A, swath 8 to section II, and swath 16 to section III.

graphic effects on aridisation. Based on sedimentological analyses carried out on deposits in the Central Depression south of 20°S latitude, Jordan et al. (2014) proposed that the sediments record a 12–11 Ma-old change towards hyperarid conditions, which they tentatively related to amplifications of rain shadow effects in response to the rise of the Andes. However, it was also suggested that the rise of the Altiplano should cause an increase in precipitation rates through a mechanism where an elevated plateau leads to stronger insolation and thus to a positive feedback between greater atmospheric convection on the Altiplano and attraction of more moisture from the Amazon basin (Strecker et al., 2007). If correct, then sedimentary archives with sources in the Western Cordillera and the adjacent Altiplano Plateau are expected to record an increase in available moisture and precipitation rates and not a shift towards drier conditions. It is the scope of this paper to explore this hypothesis and to propose a mechanism for explaining possible spatially variable responses.

Here, we investigate stratigraphic records of precipitation change in the Andes of Northern Chile. We focus on the time span between c. 25 Ma and the present when the Andes rose to elevations high enough to modify and intercept moisture pathways (Strecker et al., 2007; Ehlers and Poulsen, 2009), and when the protrusion of the Andean foothills on the eastern margin, as revealed by e.g., Kley et al. (1997) and Eichelberger et al. (2013), could have deviated the moisture source farther to the east. Our investigations focus on stratigraphic archives of material deposited in the western Andean margin, but derived through erosion from the Western Cordillera (Figs. 1, 2). We use the sedimentary structures of these deposits to reconstruct spatio-temporal shifts of precipitation rates in the source areas. We conclude that in the Western Andean margin of Chile, the modern N–S precipitation gradient and related water budgets (Fig. 1) have been recorded since as early as 12–11 Ma, and that the establishment of this gradient might have been conditioned by the history of crustal deformation of the eastern Andean margin and particularly in response to the rise of the Altiplano Plateau.

2. Setting

In northern Chile, the western margin of the Andes represents a gently folded ramp that connects the Pacific coast with the Western Cordillera, which forms the modern arc and hosts andesitic stratovolcanoes of Miocene to modern ages (Wörner et al., 2000). The Altiplano, situated east of the Western Cordillera (Fig. 1), is a highly elevated plateau with gentle hills at approximately 4 km a.s.l. and extends ca. 2000 km in N–S direction and 400 km across strike. The Coastal Cordillera (labeled as 'CC' on Fig. 2) delineates the Andean margin to the west adjacent to the Pacific Ocean. In northern Chile, this morphotectonic domain is underlain by Mesozoic tholeiitic arc rocks and marine backarc sediments (Allmendinger et al., 2005; García and Hérail, 2005). The Central Basin situated between c. 18°–19°S in the Tacna–Arica area (Fig. 2), and the Central Depression north of c. 20°S host an Oligo/Miocene suite of volcano-sedimentary rocks derived from the Western Cordillera (see e.g. Madella et al., 2017). Both sedimentary basins are located between the Coastal Cordillera and the Western Cordillera. Mapping reveals that the Central Basin comprises the Azapa (Az on Fig. 2), Oxaya (Ox), and El Diablo Formations (ED), while the time equivalent deposits in the Central Depression are mainly referred to as the Alto de Pica Formation (AdP on Fig. 2) (Farías et al., 2005; Jordan et al., 2014). On the foothills of the Western Cordillera, locally-sourced deposits are preserved in the Late Miocene Huyalas Formation in the Arica region (18°S latitude, Hy on Fig. 2; García et al., 2004), in the Lauca Basin on the eastern margin of the Western Cordillera (Fig. 2; Gaupp et al., 1999), and in the what has been referred to as the 'Piedmont unit' by Jordan et al. (2014) in the Alto de Pica area at c. 22°S.

The depositional surfaces particularly of the Oxaya, El Diablo and Alto de Pica Formations form pediplains or 'pampas' that can be correlated several tens of kilometers along strike. The pampas have been incised by perennial and ephemeral streams with sources on the Altiplano and in the Western Cordillera since ca. 11 Ma or possibly later (Hoke et al., 2007; Jordan et al., 2010), leading to the formation of >1500 m deep valleys or 'Quebradas'. Progressive downcutting also resulted in the accumulation of strath terrace conglomerates, particularly in the Lluta valley at 18°S (Fig. 2).